

MECHANICAL VIBRATION MEASUREMENT

E.P. APPERT



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by

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## PREFACE

In the calibration of mechanical vibration pickups the accuracy of the calibration depends upon how accurately the displacement of the pickup can be measured.

This thesis has been a study into the feasibility of calibrating vibration pickups by means of an optical interferometer system. The unit used in the study was designed by Professor E. K. Gatcombe in 1952 and work was done by this author from January 1953 through May 1953 at the United States Naval Postgraduate School, Monterey, California.

The author is indebted to Professor Gatcombe for his valuable guidance throughout the entire work and to Professor S. H. Kalmbach for his helpful assistance. Grateful acknowledgement is due to Joe Oktavec for the excellence of the machine work involved.



# TABLE OF CONTENTS

	Page
Certificate of Approval	i
Preface	ii
Table of Contents	iii
List of Illustrations	v
Table of Symbols and Abbreviations	vi
Chapter I Summary	1
1. Introduction	1
2. Objective of this Thesis	1
3. General Methods Employed	1
4. Findings	3
Chapter II Theory of Interferometer Operation	4
Chapter III Design Considerations and Changes Required	6
1. Original Unit	6
2. Mercury Light Source	6
3. Quartz Flats	7
4. Photoelectric Tube	10
Chapter IV Interpretation of the Results	12
1. Phototube Output	12
2. Accelerometer Output	12
3. Presentation of the Outputs	12
Chapter V Results	14
1. Test Runs	14
2. The Test Unit	14
3. Accelerometer Calibration	14

1	Introduction of the subject
11	History
11	Scope of the subject
7	Importance of the subject
14	Scope of the subject and its branches
1	Chapter I: General
1	1. Introduction
1	2. Objectives of the subject
4	3. General scope and importance
3	4. Methods
4	Chapter II: Theory of the subject
7	Chapter III: Design, construction and design subjects
1	1. Introduction
1	2. General design subjects
7	3. Design theory
10	4. Construction theory
15	Chapter IV: Application of the subject
15	1. Introduction
15	2. Application theory
15	3. Application subjects
15	4. Application of the subject
15	Chapter V: Results
15	1. Introduction
15	2. Results
15	3. The results
15	4. Application of the results

## TABLE OF CONTENTS (con't)

	Page
Chapter VI Conclusions	16
1. Feasibility of the Method	16
2. Suggestions for further study	16
Appendix I	17
Bibliography	21



# LIST OF ILLUSTRATIONS

		Page
Figure 1	Diagram of interferometer unit	2
Figure 2	Fabry-Perot interferometer	4
Figure 3	Haidinger fringe pattern	5
Figure 4	Haidinger fringe intensity contours	8
Figure 5	Intensity of transmitted light	9
Figure 6	Standard spectral response, S-4	11
Figure 7	Interferometer output	13
Figure 8	Test setup	18
Figure 9	Calibration unit	19
Figure 10	Oscillograph wave patterns	20

Page		Figure
1	Diagram of laboratory set	Figure 1
4	Diagram of laboratory set	Figure 2
5	Diagram of laboratory set	Figure 3
6	Diagram of laboratory set	Figure 4
7	Diagram of laboratory set	Figure 5
11	Diagram of laboratory set	Figure 6
12	Diagram of laboratory set	Figure 7
13	Diagram of laboratory set	Figure 8
14	Diagram of laboratory set	Figure 9
15	Diagram of laboratory set	Figure 10



# TABLE OF SYMBOLS AND ABBREVIATIONS

d	Distance between optical flats.
n	An integer greater than zero.
$\lambda$	Wavelength of light source.
$\psi$	Angle of incidence and refraction.
$\text{\AA}$	Angstrom Units, $1 \text{\AA} = 10^{-8} \text{ cm.}$
mm	Millimeters.
a	Acceleration of pickup in "g".
$\omega$	Frequency of vibration in radians per second.
r	Amplitude of vibration in inches.

1. The Earth as a whole	1
2. The atmosphere	2
3. The hydrosphere	3
4. The lithosphere	4
5. The biosphere	5
6. The geosphere	6
7. The pedosphere	7
8. The atmosphere	8
9. The hydrosphere	9
10. The lithosphere	10
11. The biosphere	11
12. The geosphere	12
13. The pedosphere	13
14. The atmosphere	14
15. The hydrosphere	15
16. The lithosphere	16
17. The biosphere	17
18. The geosphere	18
19. The pedosphere	19
20. The atmosphere	20
21. The hydrosphere	21
22. The lithosphere	22
23. The biosphere	23
24. The geosphere	24
25. The pedosphere	25
26. The atmosphere	26
27. The hydrosphere	27
28. The lithosphere	28
29. The biosphere	29
30. The geosphere	30
31. The pedosphere	31
32. The atmosphere	32
33. The hydrosphere	33
34. The lithosphere	34
35. The biosphere	35
36. The geosphere	36
37. The pedosphere	37
38. The atmosphere	38
39. The hydrosphere	39
40. The lithosphere	40
41. The biosphere	41
42. The geosphere	42
43. The pedosphere	43
44. The atmosphere	44
45. The hydrosphere	45
46. The lithosphere	46
47. The biosphere	47
48. The geosphere	48
49. The pedosphere	49
50. The atmosphere	50
51. The hydrosphere	51
52. The lithosphere	52
53. The biosphere	53
54. The geosphere	54
55. The pedosphere	55
56. The atmosphere	56
57. The hydrosphere	57
58. The lithosphere	58
59. The biosphere	59
60. The geosphere	60
61. The pedosphere	61
62. The atmosphere	62
63. The hydrosphere	63
64. The lithosphere	64
65. The biosphere	65
66. The geosphere	66
67. The pedosphere	67
68. The atmosphere	68
69. The hydrosphere	69
70. The lithosphere	70
71. The biosphere	71
72. The geosphere	72
73. The pedosphere	73
74. The atmosphere	74
75. The hydrosphere	75
76. The lithosphere	76
77. The biosphere	77
78. The geosphere	78
79. The pedosphere	79
80. The atmosphere	80
81. The hydrosphere	81
82. The lithosphere	82
83. The biosphere	83
84. The geosphere	84
85. The pedosphere	85
86. The atmosphere	86
87. The hydrosphere	87
88. The lithosphere	88
89. The biosphere	89
90. The geosphere	90
91. The pedosphere	91
92. The atmosphere	92
93. The hydrosphere	93
94. The lithosphere	94
95. The biosphere	95
96. The geosphere	96
97. The pedosphere	97
98. The atmosphere	98
99. The hydrosphere	99
100. The lithosphere	100

## SUMMARY

## 1. Introduction.

An important consideration in the employment of a seismic pickup is the accuracy and reliability of the criteria set up to evaluate the response characteristics of the instrument.

In the calibration of any seismic pickup the accuracy of the calibration will be directly dependent on how accurately one knows and can describe the motion imparted to the pickup.

The methods generally employed for applying a known motion to the pickup are:

- (1) Mechanical Methods
- (2) Transfer Function Methods
- (3) Secondary Standard Methods.

The mechanical method and the transfer function method are adequate for calibrations over a narrow frequency range. Standard references are available delineating the limits of these methods.

## 2. Objective of this thesis.

This thesis is an investigation into the use of an optical secondary standard of displacement for a seismic pickup, specifically as applied to the development of an accelerometer pickup.

## 3. General Methods Employed.

Reference to figure 1 will show the schematic arrangement of the components employed in the test setup. These components include a mercury lamp, filters, a collimating lens, silvered optical flats, a condensing lens, a field stop, a photoelectric tube, and a means of visual presentation of the output of the phototube.

# 1. Introduction

It is the purpose of this book to present a systematic account of the history and development of the various sciences which have contributed to the knowledge of the human mind and its functions.

In the first part of the book we shall consider the general principles of psychology, and in the second part we shall deal with the various branches of the science, such as physiology, comparative psychology, and experimental psychology.

The author has endeavored to present the subject in a clear and concise manner, and to give a full and accurate account of the progress of the science.

## THE HISTORY OF PSYCHOLOGY

### (1) Prehistoric Period

### (2) Ancient Period

### (3) Modern Period

The history of psychology is a branch of the history of the human mind, and it is the study of the development of the various sciences which have contributed to the knowledge of the human mind and its functions.

## 2. The History of Psychology

This book is a history of the human mind, and it is the study of the development of the various sciences which have contributed to the knowledge of the human mind and its functions.

The history of psychology is a branch of the history of the human mind, and it is the study of the development of the various sciences which have contributed to the knowledge of the human mind and its functions.

## 3. General Principles of Psychology

Psychology is the science of the human mind, and it is the study of the development of the various sciences which have contributed to the knowledge of the human mind and its functions.

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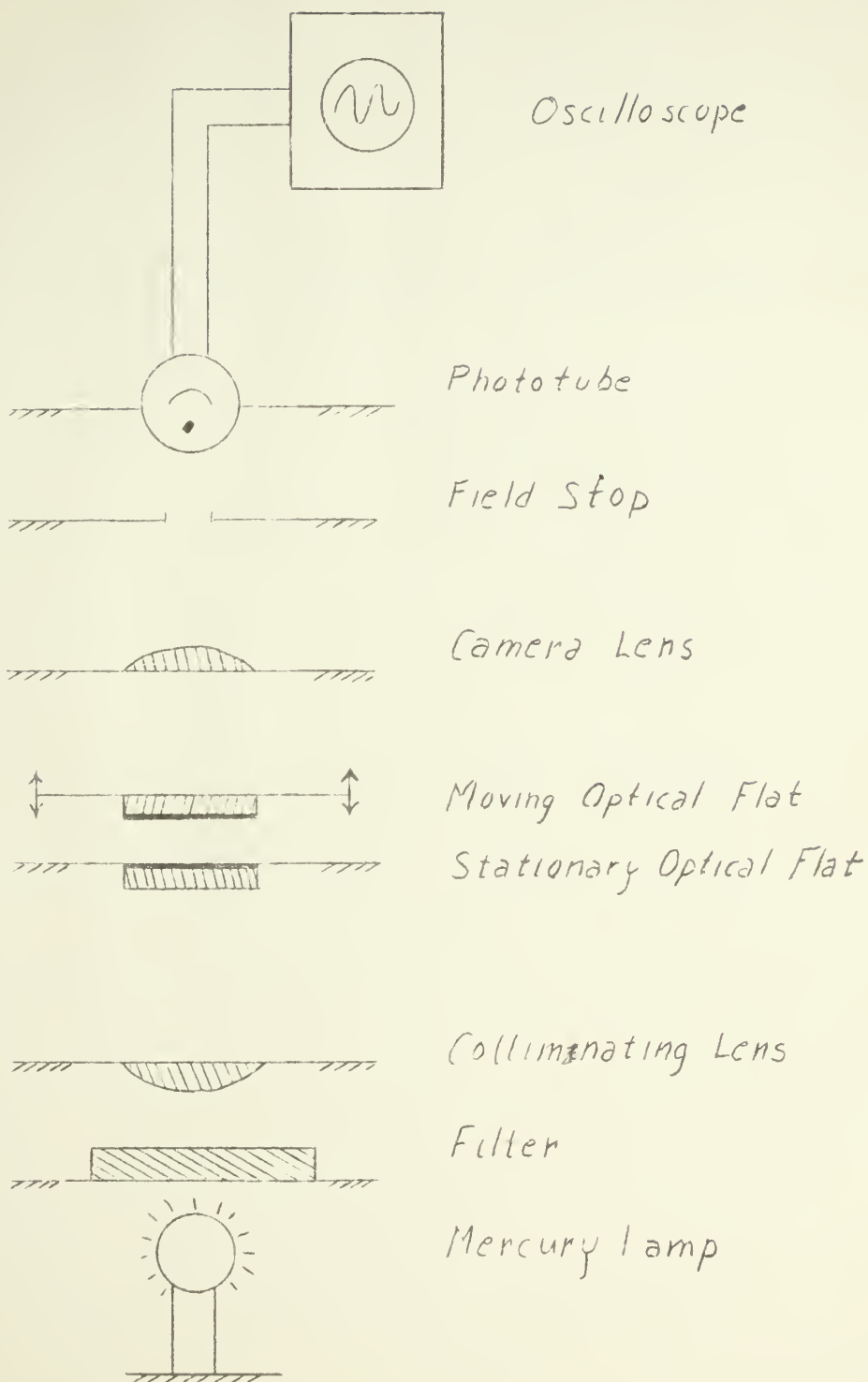


Figure 1





When the optical flats are made parallel (by external adjustments) the image of the extended source reflected in the air film between the two plane silvered flats produces the well known Haidinger fringes. A displacement of one optical flat by an amount equal to half a wavelength of the monochromatic light source will cause the central image of the fringe pattern to undergo one cyclic change as from dark to light. By proper adjustment of the optical stop and the phototube the change in the central dot will be recorded on the cathode ray oscilloscope.

In the test setup the moving optical flat is vibrated by an electromagnetic vibration inducer. The oscilloscope indicates the changes in the displacement of the optical flat per cycle of the vibration inducer.

#### 4. Findings.

The interferometer principles provide an excellent method of measuring displacements. In the calibration of pickups the calibration curve of the pickup and the amplitude response curve may be readily obtained. The apparatus is complex to build, but extremely stable once adjusted. The success of the unit is indicated by its ability to operate over a wide frequency and amplitude range.

Critical design features are the method of keeping the optical flats parallel during vibration of the moving flat, and maintaining the stationary flat without any motion.





CHAPTER II  
THEORY OF INTERFEROMETER OPERATION

The employment of Haidinger fringes in the Fabry-Perot interferometer is generally studied in an undergraduate course in optics. A brief review of the principle is given here to refresh the principles in the minds of the readers so that the design problems involved may be understood.

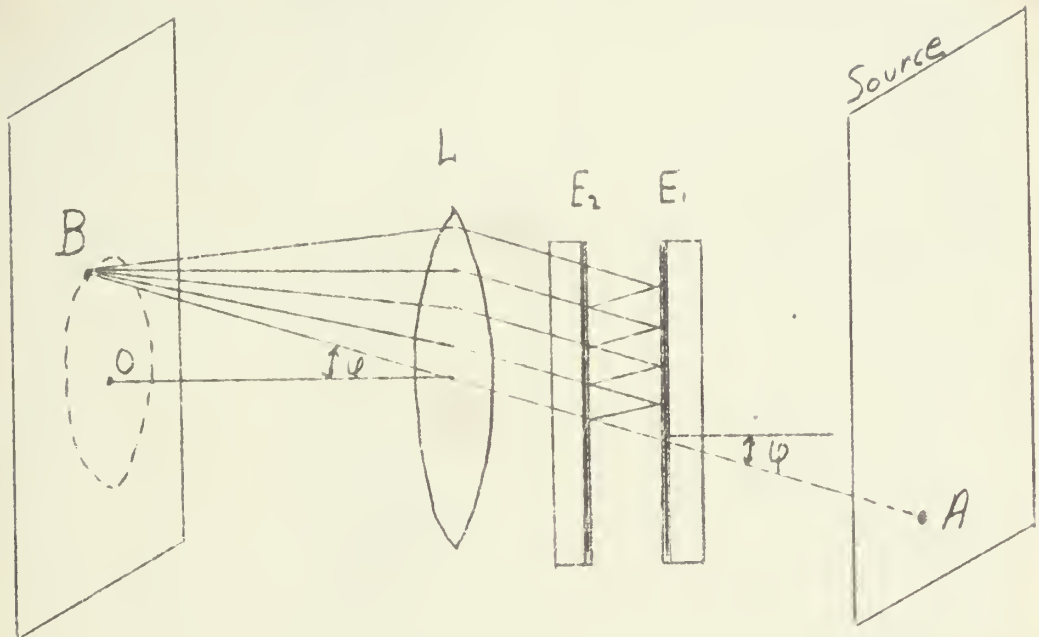


Figure 2

A monochromatic light ray from point A on the extended source transverse the silvered optical flats EE. Since the flats are parallel the multiple reflected emergent beams are all parallel to the direction of the incident ray. If the emergent beams are collected by lens L, they form at point B a part of a Haidinger fringe pattern.



The condition for reinforcement of the transmitted rays in air is:

$$2d \cos \varphi = m \lambda$$

This condition will yield a circle at O the intersection of the axis of the lens with the screen. The circle diameters are proportional to the focal length of the image-forming lens and inversely as  $\sqrt{d}$ , where d is the separation of the two flats. Altering the distance between the flats by one-half the wavelength of the light source will cause the central image of the Haidinger fringes to complete one cycle of change of the light intensity (from light to dark in the case of figure 3).

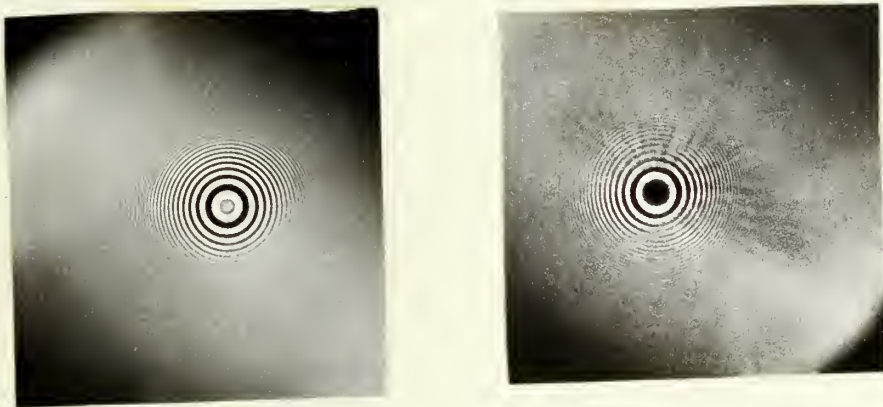


Figure 3





## CHAPTER III

### DESIGN CONSIDERATIONS AND CHANGES REQUIRED

#### 1. Original Unit.

The unit as designed by Professor Gatcombe consisted of: a Hanovia mercury light source, two quartz optical flats surfaced on the plane side with aluminum film, camera and collimating lenses of 38 mm focal length, a field stop and an RCA 1-P-42 vacuum photoelectric tube. Reference to figure 1, page 2, shows the arrangement of the components.

This original unit failed to function properly for numerous reasons, each of which will be taken up under the heading of the component involved.

#### 2. Mercury Light Source.

The obvious choice for monochromatic light in interferometry is the green light of the mercury arc with a wavelength of  $5461\text{\AA}$ . The mercury light source is readily available as are the required filters to render the light almost perfectly monochromatic. These advantages outweigh the disadvantages of lowered intensity than higher frequencies and the reduced response of commercial phototubes to this wavelength.

In operation of the unit the Hanovia mercury light failed to operate satisfactorily. The bulb being of the high pressure design rapidly heated up and introduced pressure broadening effects which caused the Haidinger fringe pattern to disappear. This problem was rectified by the purchase from the R & M Company of Pasadena, California of a special low pressure mercury light arranged in a

THEORY OF THE LIGHT SOURCE

1. General Theory.

The light is assumed to be emitted by a

source which is at rest in the frame of reference

in which the observer is at rest. The source is

assumed to be a point source, and the light is

assumed to be emitted in all directions.

2. The Source.

The source is assumed to be a point source, and

the light is assumed to be emitted in all

directions.

3. The Observer.

The observer is assumed to be at rest in the

frame of reference in which the source is at rest.

The source is assumed to be a point source, and

the light is assumed to be emitted in all

directions.

4. The Observer's Motion.

5. The Source's Motion.

6. The Observer's Acceleration.

7. The Source's Acceleration.

8. The Observer's Velocity.

9. The Source's Velocity.

10. The Observer's Acceleration.

flat spiral. Care was taken in the design of the bulb that it could withstand any vibration forces that might be encountered in the calibration tests. A high intensity light is desired since the greater the intensity of the monochromatic light source the stronger the signal produced by the photoelectric tube. The space limitations of the calibration unit restricted the size of the R & M light to one of about 40 watts.

### 3. Quartz Flats.

Three important design considerations are associated with the quartz flats, viz: the sharpness of the fringes observed, the intensity of the light which arrives at the phototube, and the size of the central image at the optical stop. The successful operation of the unit depends upon satisfying these highly critical and mutual dependent requirements.

The sharpness of the fringes (distribution of intensity) has been set in classical form by Airy (Reference 3). In figure 4 is shown the intensity contours for the Haidinger fringes, showing how their sharpness depends upon the reflecting power. When the mirror surfaces reflect between 80 to 90% of the incident light the bright fringes almost equal the incident light intensity less absorption, while the dark fringes represent almost complete exclusion of the incident light.

As the reflecting coefficient approaches 100% the fringe sharpness improves, but the intensity of the light received by the phototube becomes too low to be effective. This consideration requires that the mutually contradictory factors of high reflection and high transmission be compromised. Figure 5 shows the relation



that signal. One can think of the signal as being

sent by the signal source and being received by

the signal receiver. A very important point is that the

signal is sent by the signal source and is received by the

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Three important points must be noted in this

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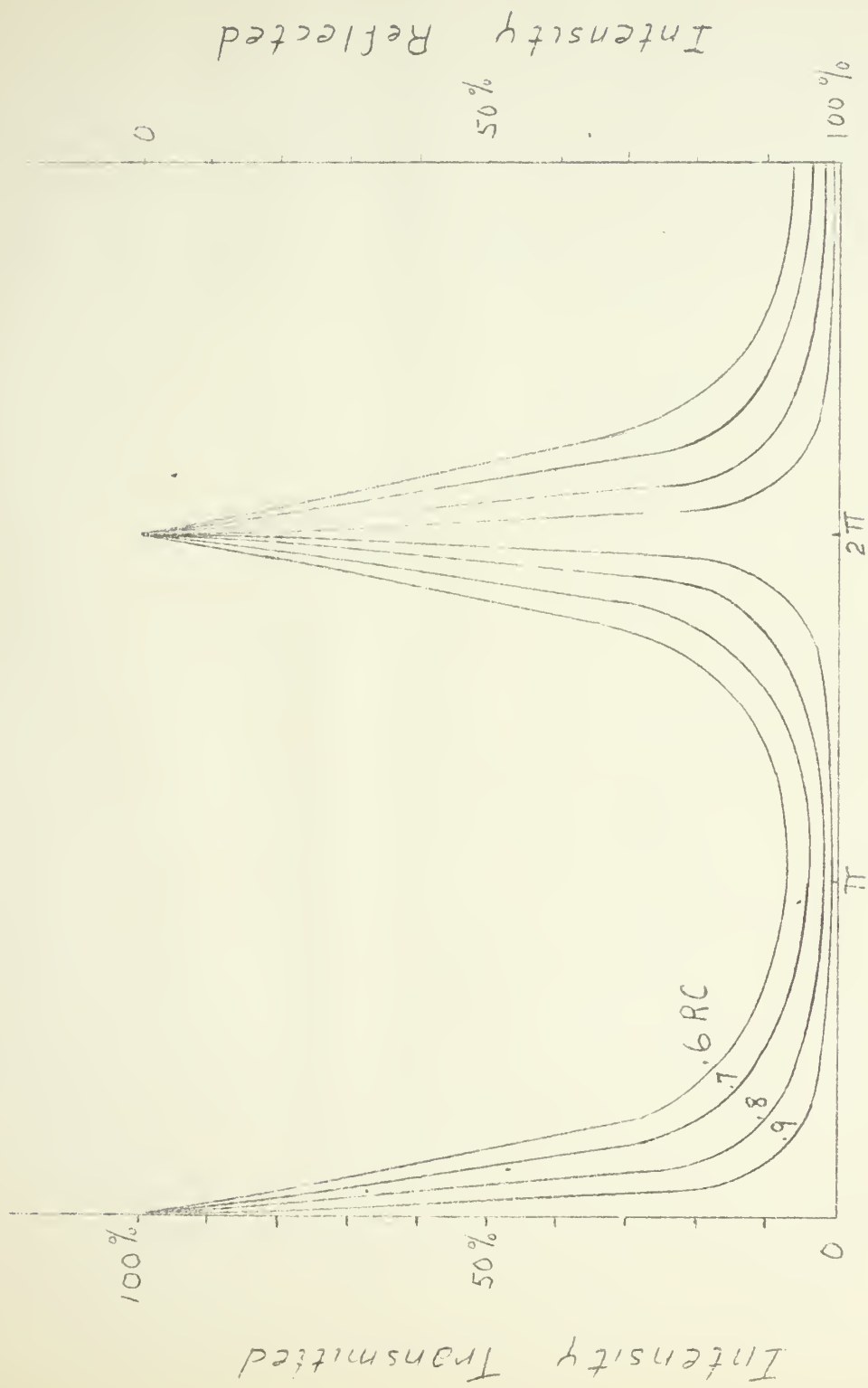


Figure 4



between the reflecting coefficient and fraction transmitted for both aluminum and silver films. A satisfactory compromise between figures 4 and 5 coupled with several experimental mirrors resulted in an 80% reflecting power coating as the most desirable for the unit involved.

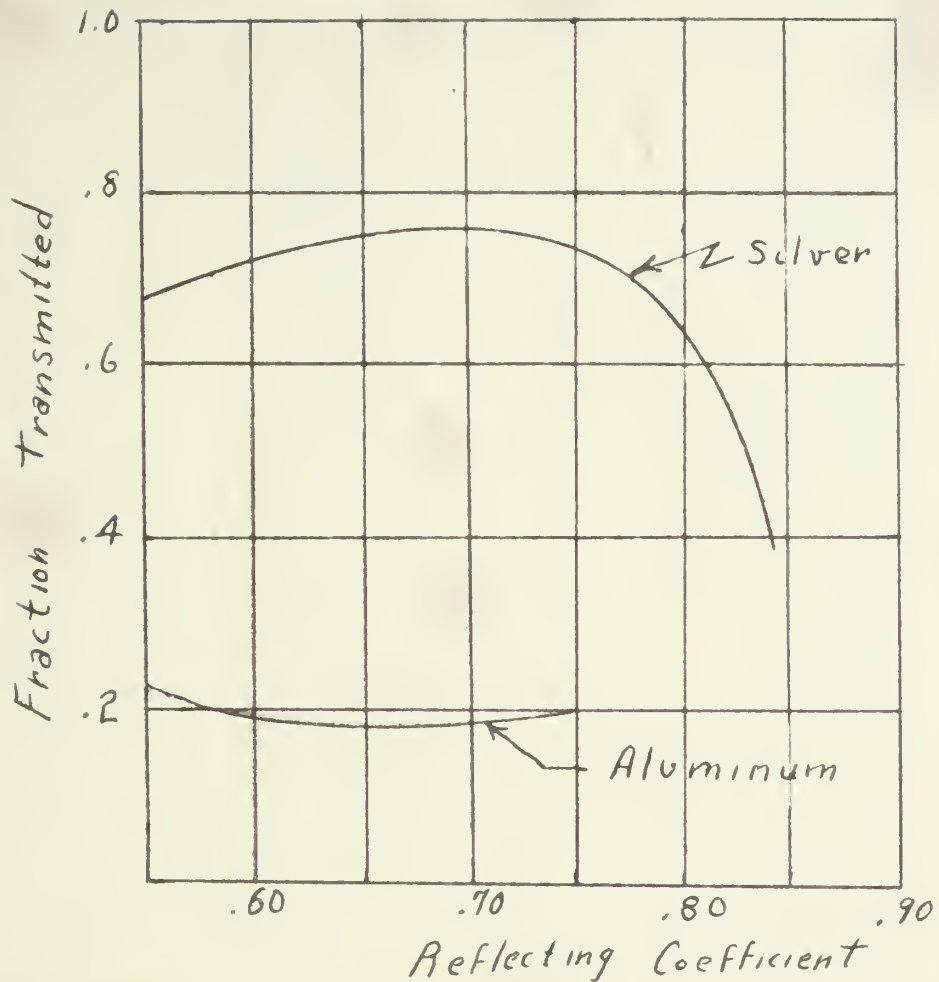


Figure 5

The original unit contained flats with aluminum mirrors. The poor efficiency of the aluminum mirror as indicated by figure 5 dictated the change to the silver mirror.

between the following conditions and the results obtained for  
each element and their effect. A satisfactory comparison between  
figures 1 and 2 would be made if the results obtained for each  
in the following cases were given as the same results for the  
same element.

The original and modified forms of the element shown. The  
new element of the element shown is indicated by figure 2.  
Revised the element to the new element.

The quartz flats were prepared for silvering by the ionic bombardment technique. The silvering was performed by evaporating the silver from a tungsten filament under a vacuum of about  $10^{-5}$  mm of Hg. To obtain optimum purity of the deposited silver thereby reducing absorption losses required the preparation of a large number of mirrors before acceptable ones were obtained.

The distance between the optical flats (d) in the original unit was 0.286 inches. This produced a central image at the focus of the condensing lens with a diameter of about 0.015 inches. In order to increase the diameter of this image the distance between the optical flats was decreased to 0.150 inches, resulting in an increase in the central image to 0.019 inches. The moving optical flat was designed to vibrate with a maximum amplitude of 0.0075 inches, giving a 100% factor of safety before flats would collide.

#### 4. Photoelectric Tube.

The original unit was designed to utilize an RCA photoelectric tube 1-P-42. This tube was chosen for its response to the 5461 Å mercury light and its desirable size. It is only about 1 inch in length by  $\frac{1}{4}$  inch in diameter with the photocathode at the end of its tubular structure. Figure 6 indicates the spectral response characteristics of the tube.

Reference again to figure 1 shows that the tube is required to pick up the light passed through the field stop and forward it to the recording instrument. The tube performed this specific function satisfactorily, and did transmit a signal indicating a change in the central image from a bright to a dark image. However, even after the changes to the mercury light and to the optical

The original was not changed in any way.



flats the intensity of the light which the phototube received resulted in a current flow of the order of  $10^{-10}$  amperes. This current flow was so low that it was difficult to distinguish between the noise of the electronic equipment and the signal output of the phototube. Since the unit as originally built left no room for a larger phototube, the entire physical structure of the assembly was changed to accommodate a photomultiplier tube.

The photomultiplier chosen, the RCA 1-P-21, has the same spectral response as the 1-P-42 (figure 6). This tube is capable of producing a maximum current amplification of 2,000,000 at an applied voltage of 100 volts per stage. Since amplification was now accomplished in the phototube, the reduction in the noise level resulted in a relatively low noise to signal ratio at the recording instrument.

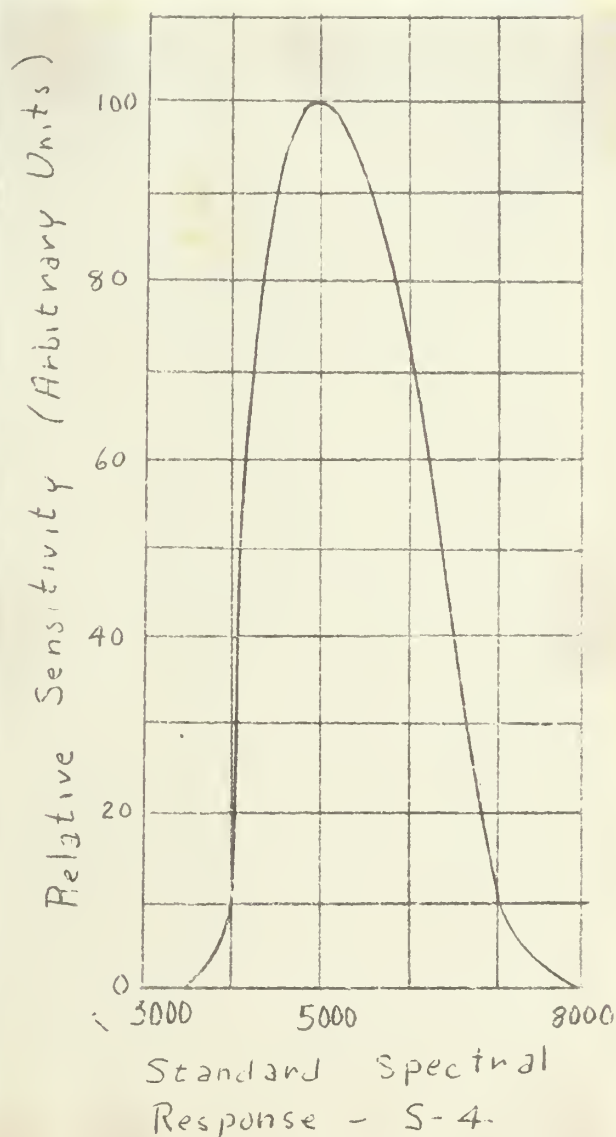


Figure 6

The first laboratory of the field which the present report re-  
 sults from a current flow of 100 amperes at 100 volts. This  
 current flow was so low that it was difficult to distinguish be-  
 tween the effect of the electrical equipment and the effect of the  
 of the electrodes. When the first set of electrodes was used in the  
 low a larger electrode, the effect of the electrodes was more  
 marked and it was found that the electrodes were more effective.

The present report  
 shows, also, that the  
 has the same effect  
 response as the first  
 (figure 2). This was  
 in spite of the fact  
 a second current was  
 of 1,000,000 in  
 an applied voltage of  
 100 volts per second.  
 When the electrodes were  
 now separated in the  
 solution, the re-  
 sults in the same level  
 resulted in a similar  
 low value to the  
 level of the electrode



## CHAPTER IV

### INTERPRETATION OF THE RESULTS

#### 1. Phototube Output.

Each time the separation between the optical flats is changed by one-half of the wavelength of the mercury light source the central image of the Haidinger fringe completes one cyclic change. For the mercury line  $5461\overset{\circ}{\text{Å}}$  this corresponds to a change of 0.00001071 inches in the separation of the plates. If the moving optical flat is vibrating at 1000 cycles per second through an amplitude of 0.0001 inches the phototube will be acted upon by a change in light cycles equal to

$$4\pi \times 1000 \frac{0.0001}{0.00001071} \quad \text{or} \quad 37355 \text{ cycles per second.}$$

#### 2. Accelerometer Output.

If an accelerometer is attached in some manner to the moving optical flat this amplitude and frequency would correspond to an acceleration of:

$$a = r \omega^2 = \frac{0.0001}{12} (1000 \times 2\pi)^2 = 328g$$

Correlation of the accelerometer output with the output of the phototube yields a true calibration for the accelerometer.

#### 3. Presentation of the Outputs.

Figure 8 shows the test setup. The output of the phototube is displayed on the Y axis of the Cathode Ray Oscilloscope. When the time sweep of the oscilloscope is made equal to the one vibration of the unit, the number of peaks on the curve in one cycle will equal the number of changes in distance between the optical flats in units of half wave lengths of light. See figure 7. By

THEORY OF THE CURVE

1. Introduction.

Let us first consider the case in which the curve is a straight line. In this case the equation of the curve is of the form  $y = mx + c$ , where  $m$  and  $c$  are constants. The curve is a straight line if and only if the equation of the curve is of this form.

For the case in which the curve is a circle, the equation of the curve is of the form  $x^2 + y^2 + 2gx + 2fy + c = 0$ , where  $g$ ,  $f$ , and  $c$  are constants. The curve is a circle if and only if the equation of the curve is of this form. The radius of the circle is  $\sqrt{g^2 + f^2 - c}$  and the center is  $(-g, -f)$ .

$$\text{The radius of the circle is } \sqrt{g^2 + f^2 - c} \text{ and the center is } (-g, -f).$$

2. The equation of the curve.

Let us now consider the case in which the curve is a parabola. In this case the equation of the curve is of the form  $y = ax^2 + bx + c$ , where  $a$ ,  $b$ , and  $c$  are constants. The curve is a parabola if and only if the equation of the curve is of this form.

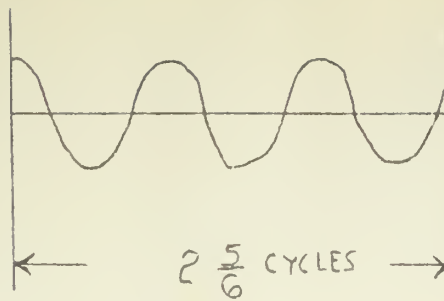
$$y = ax^2 + bx + c \quad \text{where } a, b, \text{ and } c \text{ are constants.}$$

Let us now consider the case in which the curve is an ellipse. In this case the equation of the curve is of the form  $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ , where  $a$  and  $b$  are constants. The curve is an ellipse if and only if the equation of the curve is of this form.

3. The equation of the curve.

Let us now consider the case in which the curve is a hyperbola. In this case the equation of the curve is of the form  $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$ , where  $a$  and  $b$  are constants. The curve is a hyperbola if and only if the equation of the curve is of this form. The asymptotes of the hyperbola are the lines  $y = \pm \frac{b}{a}x$ .

this method one may immediately determine the amplitude of displacement occurring in an accelerometer which vibrates through the same displacement as the moving optical flat.



*Interferometer Output*

Figure 7



THESE ARE THE  
RESULTS OF THE  
OBSERVATIONS  
MADE AT THE  
OBSERVATORY  
OF THE  
UNIVERSITY OF  
CHICAGO  
DURING THE  
MONTH OF  
JANUARY  
1891

THESE ARE THE  
RESULTS OF THE  
OBSERVATIONS  
MADE AT THE  
OBSERVATORY  
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UNIVERSITY OF  
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DURING THE  
MONTH OF  
JANUARY  
1891



## CHAPTER V

### RESULTS

#### 1. Test Runs.

Figure 9 shows a composite of photographs taken during test runs. The runs were made at several frequencies and amplitudes of vibrations. The variation of the central image is super-imposed on a 60 cycle wave. By utilizing the 60 cycle wave as a time base, and knowing the frequency of vibration one may readily count the "pips" and ascertain the number of halfwave length changes in displacement between the optical flats.

Had a D.C. mercury light source been used the time base could be the frequency of the vibration. The photographs would then be as in figure 7. Lack of a 3000 volt D.C. supply voltage prevented the author from using this more direct approach.

#### 2. The Test Unit.

The unit used in this investigation easily complied with all the criteria by which we judge a measurement standard:

- a. It has a wide frequency and amplitude range.
- b. It is extremely stable as regards time, temperature and rugged use.
- c. It does not introduce any harmonic distortion.
- d. The output is related to the mechanical motion only.
- e. It is simple to use and easy to calibrate.

#### 3. Accelerometer Calibration:

The accelerometer calibration is obtained by recording the voltage across the bridge circuit of the transducer in the commercial type strain gage accelerometer. Calibration curves





obtained directly are: (1) amplitude of vibration vs. accelerometer output at constant frequency and (2) frequency vs. accelerometer output per "g". No calibration runs were actually made.

output per sq. ft. of available area was 1000 lbs. per acre.

## CHAPTER VI

### CONCLUSIONS

#### 1. Feasibility of the Method.

The author is of the opinion that an optical standard for the measurement of small displacements can be successfully employed to calibrate seismic pickups to an accuracy of within one percent. (See appendix I). The unit used in the thesis work is extremely stable and capable of operation over a wide range of frequencies and amplitudes. As with any unit of a new design there are features which require further study and improvement to make the unit more than an experimental laboratory test piece. Of particular importance is to reduce the degree of mechanical coupling between the moving flat and the stationary flat, and to increase the intensity of the mercury lamp.

#### 2. Suggestions for further study.

Improvements in the electronic arrangements for the calibration tests are a fertile field of study. The limitations of thesis time prevented building special circuits for measuring the outputs involved. Of great value in the calibration would be a circuit to record transient variations in the displacement and in the accelerometer output. The study of transient accelerometer measurements represents a field all too long neglected, and this unit coupled with an electron counting circuit would afford a comparatively direct means of investigating the phenomenon.



## APPENDIX I

### ERROR CONSIDERATIONS

Assume the output of the phototube as shown by the scope is  $9 \frac{5}{6}$  cycles of a sine wave pattern. For mercury light of  $5461 \text{ \AA}$  the displacement of the plate is:  $9 \frac{5}{6} \times \frac{5461}{2}$  or  $26845 \text{ \AA}$ .

If the number of cycles on the scope is read to the nearest  $30^\circ$  the accuracy of the measurement is plus or minus  $1/24$  the oscilloscope cycle or  $11 \frac{1}{4} \text{ \AA}$ .

The error for this displacement (about .0001 inches) corresponds to:  $\frac{11 \frac{1}{4}}{26845}$  or 0.42%.

Obviously for smaller displacements the errors are larger and vice versa.

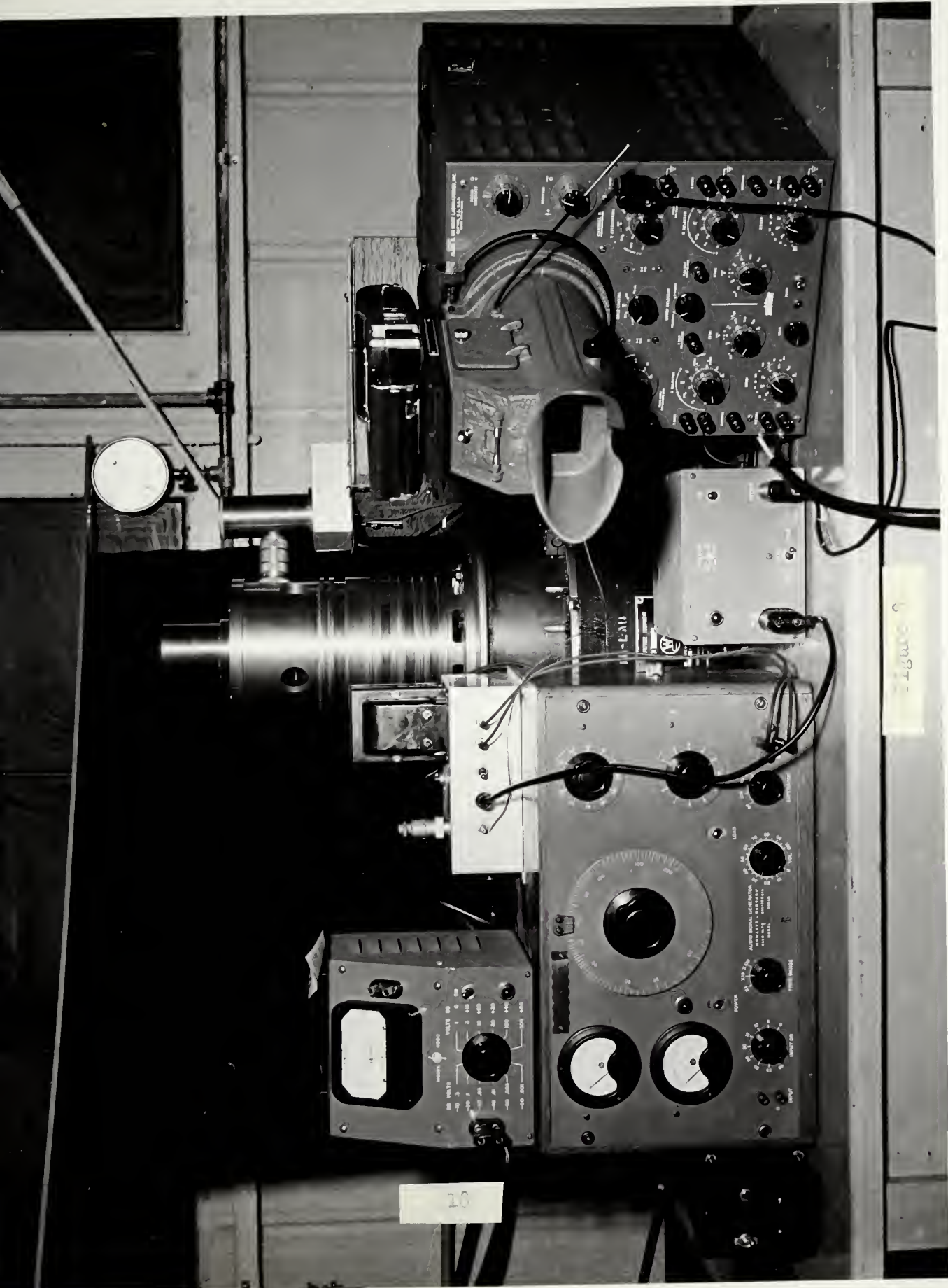
Another source of error is in the frequency measurements. There are available standards of frequency measurement accurate to within 0.1% or less, so that this error is almost negligible.

In actual work one might anticipate slightly higher errors, possibly due to slight vibrations of stationary optical flat. However, it is not anticipated that the error would total more than 1% in any measurement made.









THE CHIEF OF OPERATIONS

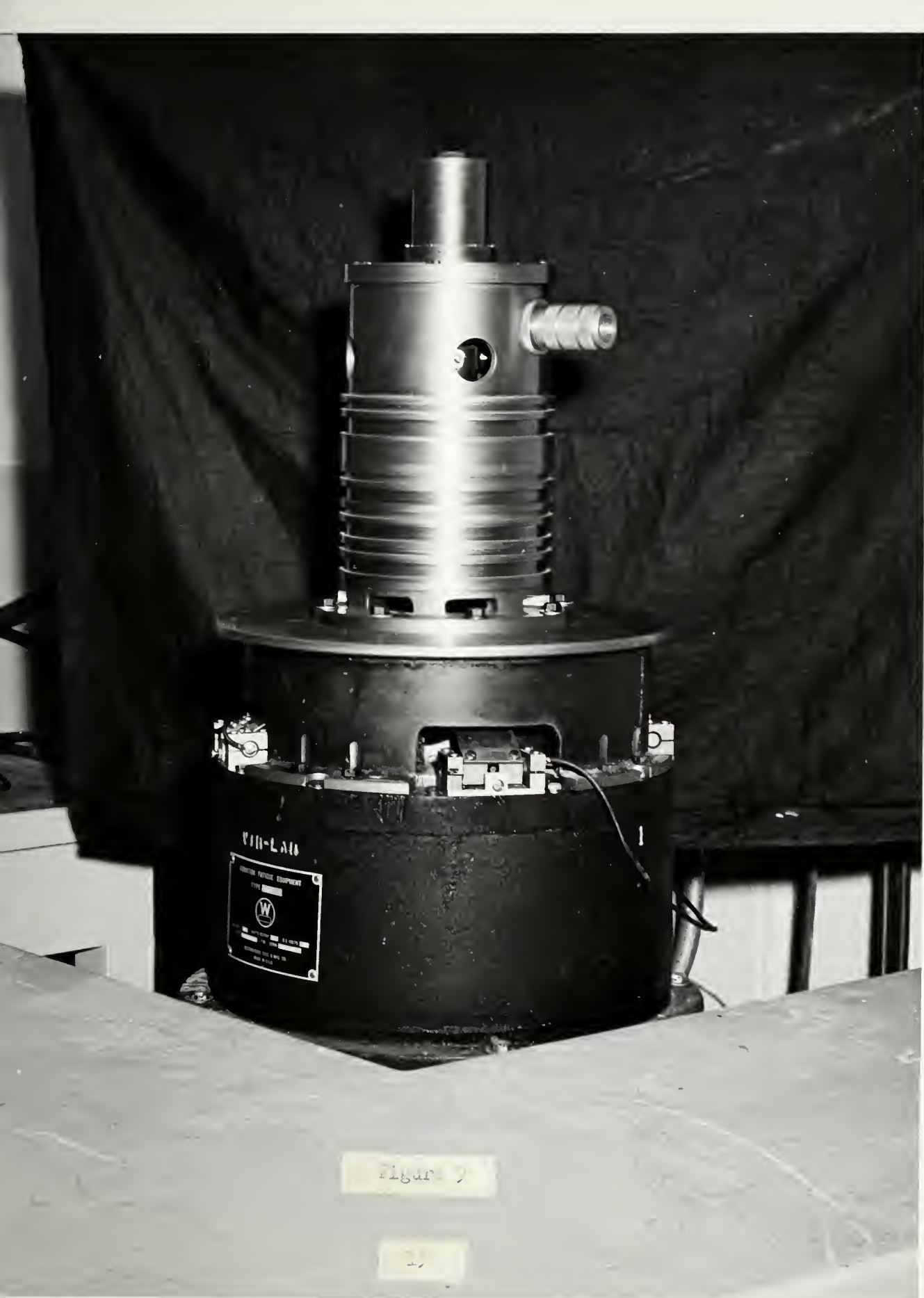


Figure 7

OFFICIAL PHOTOGRAPH  
NOT TO BE USED FOR PUBLICATION  
OF THE  
THE CHIEF OF POLICE OPERATIONS





Figure 20





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